

## A CEMENT TREATED BASE COMPOSITION

The present invention relates to a cement treated base composition and its method of manufacture. In particular, the present invention relates to a composition for a Cement  
5 Treated Base.

The invention may be used in the construction industry for preparing in-place soil-cement or for mixing haul-in soil-cement commonly used for the base layer under Portland cement concrete or asphalt concrete roads, parking lots, runways, taxiways, aprons and the like; and  
10 in the construction of land fill containment bases and dikes. Soil-cement in this definition includes in-place native soil, natural aggregate such as gravel, processed aggregate such as washed sand, and waste or reclaimed material such as reground asphalt road bed. The process of incorporating cement into road base material is commonly known as Cement Treated Base or "CTB" operations.

15 Cement Treated Base (CTB) is a general term that applies to an intimate mixture of native soils and/or manufactured aggregates (fines) with Portland cement and water. Other descriptions such as soil-cement, cement-treated aggregate base, cement-stabilized roadbed, and cement stabilized base are sometimes used.

20 CTB has several cost saving advantages over conventional bases. First, CTB provides a stiffer and stronger base than conventional base materials. This both delays the onset of common surface distresses, including fatigue induced cracks, and prolongs the life of the pavement system. In addition, due to the higher loading capacity, the thickness of CTB layers can often  
25 be reduced in comparison to conventional bases while still carrying the same traffic. Finally, the use of local soils or in-place materials is often possible with CTB, which can significantly reduce material hauls.

Construction methods for preparing a base for a road bed or the like before CTB operations  
30 commence, vary considerably with intended use, strength requirements, and whether it is a new construction or rehabilitation of an old road. CTB operations start when the base material

(native soil, subsoil, plus any haul-in aggregates and/or reclaimed material) are placed to specified depth and grade.

Portland cement owes most of its strength producing properties to hydration, a process where liquid water combines with the cement to form hydration products. Thus, the most efficient use of the cement (of highest strength) in respect to the amount of cement used is attained when mixing, shaping, grading and compaction are complete before a significant amount of hydration of the cement occurs. Since moisture is in the base material and the temperature of the base material is influenced by weather conditions, large variations in the strength produced can occur when using dry cement addition. The lack of sufficient time to complete compaction and finishing of the CTB and the absence of any convenient means to delay the hydration time are inherent deficiencies of using dry cement in CTB operations.

The transverse (across the roadway) cracking is the number one side effect in this three-layer road construction system. This transverse cracking is more predominant in cement treated aggregate base courses.

A typical pavement structure is shown in Fig. 1 comprising a subgrade 4 (native material upon which the pavement is built), a sub-base course 3, a base course 2, and a surface course 1. The sub-base course 3 functions as structural support of the pavement and spread the load evenly over the sub-grade. The materials used for sub-base course 3 are either unbound granular materials such as crushed stone, or cement-bound materials such as a soil-cement mixture.

The base course 2 is located between the sub-base course 3 and surface course 1. It provides a stable platform for uniform support to the pavement surface course, and additional load distribution.

The surface course 1 is the top structural layer that comes in contact with traffic loads. It contributes the most to the pavement strength and provides characteristics such as friction, smoothness, rut resistance, noise control and drainage. Moreover, it prevents surface water from entering the layers beneath. Typically for rigid pavements, the surface course is a

Portland Cement Concrete (PCC) slab, while Hot Mix Asphalt (HMA) concrete is typically used for flexible pavements.

According to the materials used, base courses can be categorised as aggregate base course, cement-treated base (CTB) course and lean concrete base course and so forth. Conventional base course materials, such as unstabilised aggregates and lean concrete, are too rigid to deform concurrently with the surface course. Compared with unstabilised aggregates, the CTB can prevent soil from the subgrade 4 or sub-base course 3 moving into the base course 2 and surface course 1. Existing CTB materials do not provide for strictly controlled rigidity or flexibility to match the certain flexibility of the surface course.

Damage (or cracking) may occur in the pavement due to the vast differences of deformation (or flexibility) between the base course and surface course over time due to use of the pavement, especially with high and heavy loading traffic. The differential warping and bending of the surface and base course leads to cracks in the pavement that will require repairs or replacement. To do so the damaged surface layer is replaced, or the base course and/or sub-base course may be replaced as well.

Airport runways and taxiways pose particular challenges. The size and weight of aeroplanes place a lot of stress and impact on the pavement compared to a typical car, especially during the landing and take-off of the aeroplane on the runway.

There are two possible pavement design for airport runways and taxiways – flexible and rigid pavement. A flexible pavement provides sufficient thickness for load distribution through a multilayer structure so that the stresses and strains in the subgrade soil layers are within the required limits. A rigid pavement is able to effect a slab action to spread the wheel load over the entire slab area. The structural capacity of the rigid pavement is largely provided by the slab itself (The Civil Engineering Handbook, Second Edition, 2002, Chapter 62 Highway and Airport Pavement Design, W.F. Chen, J.Y. Richard Liew).

In a flexible pavement design, the surface course 1 is typically a hot mix asphalt wearing surface placed on a base course 2, and when required by subgrade conditions, a sub-base

course 3. The base course 2 is the principal structural component of the flexible pavement, and is divided into two major types – stabilised and unstabilised base courses. The US Federal Aviation Authority (FAA) requires stabilised base course 2 and sub-base course 3 for new flexible pavements designed to accommodate jet airplanes weighing 100,000 pounds (45,359 kg) or more, with some exceptions allowed. This includes most commercial aircraft that seats more than 100 people and similar sized cargo aircraft.

Generally, the stabilised base courses can be further divided into stabilised-flexible and stabilised-rigid. The term flexible is used to indicate that these bases have a higher Poisson's ratio, act as flexible layers and are less likely to crack than rigid stabilised bases. The stabilised-flexible base course materials include Plant mix bituminous pavements (P-401) and hot mixed asphalt base course (P-403). The stabilised-rigid base course materials include cement treated base course (P-304), and econocrete subbase course (P-306). The standard FAA bituminous base is P-401/P-403 which has a modulus of 400,000 psi (2.76 GPa). A normal cement treated base P-304 has a modulus of 500,000 psi (3.45 GPa). The stabilised-flexible base course material is more flexible but weaker in strength, and requires a thicker layer to compensate for the lack of strength. A thicker base course 2 layer will require more materials, and more time to lay and compact the layer.

The typical elastic modulus of a rigid pavement made of Portland cement concrete (PCC) and a flexible pavement made of asphalt concrete is about 25 GPa to 35 GPa and 2 GPa to 3.5 GPa respectively.

A rigid pavement uses a Portland Cement Concrete pavement as the surface course 1. A rigid pavement is considered to be a runway, taxiway, or ramp that is surfaced with a mixture of concrete materials (Portland cement, sand, coarse aggregate and water) of from 6 to 20 inches (152.4 mm to 508 mm). A runway that serves wide body aircraft usually has a concrete thickness of 17 to 20 inches (431.8 mm to 508 mm). Joints are usually provided in the rigid pavement to allow for temperature variations. A base course 2 can be provided as well to provide additional load distribution, provide drainage and frost resistance, and prevent fine soil from the subgrade 4 from entering the pavement structure. However, the requirement

of the base course 2 is less stringent since it is the surface course 1 that takes the most of the load.

The choice of a flexible or rigid pavement each has their own advantages and disadvantages, and depends on the environmental conditions and costs amongst others. A flexible pavement is generally cheaper to construct than a rigid pavement but more costly to repair due to the layered structure. A flexible pavement can expand and contract more easily in response to the temperature while a rigid pavement requires expansion joints and careful design of the pavement surface to accommodate temperature differences.

For a road or highway, a portion of the affected pavement could be closed and repairs carried out. However, for a runway or taxiway such repair works will necessitate the closure of the entire runway or taxiway affecting the airport operations. Since most airports have a limited number of runway and taxiways available, closure of a runway or taxiway for a long period of time is not desirable and results in large economic cost for the operators and passengers.

Existing CTB courses have the structural strength but not the flexibility of the stabilised-flexible base course 2.

Therefore, there is a need for a CTB that provides the necessary strength to support the pavement above it and yet have the flexibility to flex together with the pavement to provide the necessary movement.

The listing or discussion of an apparently prior-published document in this specification should not necessarily be taken as an acknowledgement that the document is part of the state of the art or is common general knowledge.

Any document referred to herein is hereby incorporated by reference in its entirety.

In a first aspect of the present invention, there is provided a method of preparing a cement treated base composition, the method comprising: (a) providing an amount of aggregate material and an amount of cementitious material, the aggregate material and cementitious

material having a combined dry mass; (b) mixing the aggregate material and the cementitious material; and (c) if necessary, providing an amount of water to the mixture to form a composition having a moisture content of between 7.0wt% and 10.5wt% of the combined dry mass.

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Preferably, the moisture content of the composition is between 8.0wt% to 9.0wt% of the combined dry mass.

10 The moisture content of the composition is determined by a compaction curve, i.e. a moisture-density relationship curve, as will be shown in detail further below.

Preferably, the amount of cementitious material present in the composition is between 2.0wt% to 6.0wt% of the aggregate material, i.e. the amount of cementitious material to aggregate material is 2:100 to 6:100. More preferably, the amount of cementitious material  
15 present in the composition is between 3.0wt% to 5.0wt% of the aggregate material, i.e. the amount of cementitious material to aggregate material is 3:100 to 5:100.

The following provide examples of the proportions of the aggregate material vs the amount of cementitious material present in the composition and their corresponding total optimum  
20 moisture content.

- (a) 100 parts of aggregate and 3.0 parts of cement with a moisture content of 8.5wt% of the combined dry mass of both the aggregate and the cement
- (b) 100 parts of aggregate and 3.5 parts of cement with a moisture content of 8.5wt% of  
25 the combined dry mass of both the aggregate and the cement
- (c) 100 parts of aggregate and 4.0 parts of cement with a moisture content of 8.5wt% of the combined dry mass of both the aggregate and the cement
- (d) 100 parts of aggregate and 5.0 parts of cement with a moisture content of 8.8wt% of the combined dry mass of both the aggregate and the cement.

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By “cement treated base composition”, it is meant to refer to any pastes, mortars, grouts such as oil well cementing grouts, and concrete compositions comprising a hydraulic cement binder. The terms "paste", "mortar" and "concrete" are terms of art: pastes are mixtures composed of a hydraulic cement binder (usually, but not exclusively, Portland cement, Masonry cement, or Mortar cement and may also include limestone, hydrated lime, fly ash, blast furnace slag, and silica fume or other materials commonly included in such cements) and water; mortars are pastes additionally including fine aggregate, and concretes are mortars additionally including coarse aggregate. The cement treated base compositions tested in this invention are formed by mixing required amounts of certain materials, e.g., a hydraulic cement, water, and fine or coarse aggregate, as may be applicable to make the particular cement blend being formed.

By “aggregate”, it is meant to include any coarse granular material. In particular, the coarse granular material may be typically used in construction and may include sand, gravel, crushed stone, slag, recycled concrete and geosynthetic aggregates. These aggregates may be a component of composite materials such as concrete and asphalt concrete and serve as reinforcement to add strength to the overall composite material. In other words, aggregates are used as a stable foundation or road/rail base with predictable, uniform properties (e.g. to help prevent differential settling under the road or building), or as a low-cost extender that binds with more expensive cement or asphalt to form concrete.

By “cementitious material”, it is meant to include any material that holds concrete together. These materials include traditional Portland cement and other supplementary cementitious materials (SCMs), such as fly ash, ground granulated blast furnace slag (GGBS), limestone fines and silica fume. These materials are either combined at the cement works (to produce a composite cement) or at the concrete mixer when the concrete is being produced (the cementitious product is called a combination in this case).

By “wt%”, it is meant to refer to the percentage by weight or mass or volume as the case may be. In the present case, the amount of cement to dry aggregate ratio, may be 3.0:100, 3.5:100, 4.0:100 or 5.0:100 (i.e. 3.0%, 3.5%, 4.0%, 5.0% respectively), by weight of the dry aggregate

compared to the cement, were first determined. Water is then added to the mixture of cement-aggregate to determine the moisture-density relations, the compaction curve.

For example, the mass ratio of cementitious material to aggregate is calculated by dividing the weight of cementitious material by the weight of the dry aggregate material, e.g. 69kg of cementitious material/1967kg of aggregate material = 0.035 = 3.5%. Total moisture content is then calculated by dividing the weight the water by the total dry solid mass of the cementitious material and the aggregate material, e.g. 173kg of water/(69kg+1967kg) = 173/2036 = 8.5wt%. Here, 2036kg/m<sup>3</sup> is also the maximum dry density of the CTB composition which is determined from the moisture-density relations curve (compaction curve). The amount of water (173kg provided in the example) represents the total amount of water present in the cementitious material and aggregate material, taking into account any water content that is already inherent in the aggregate material as a raw material / ingredient used in the preparation of the composition.

Preferably, the mass ratio of cementitious material to dry aggregate material is between 2.0wt% to 8.0wt%. More preferably, the mass ratio of cementitious material to dry aggregate material is between 2.0wt% to 6.0wt%; and the total water content present in the composition is between 7.0wt% to 10.5wt% of the total mass of dry solid of the cementitious material and aggregate.

More preferably, the mass ratio of cementitious material to dry aggregate material is between 3.0wt% to 5.0wt%; and the total water content present in the composition is 8.5 wt% by the total mass of dry solid (cementitious materials + aggregate) for cement percentage from 3.0wt% to 4.0wt%, and 8.8wt% for cement percentage of 5.0wt%.

Preferably, the aggregate material has a particle size distribution in weight percentage of the aggregate material as follows:

- (a) 100% smaller than 51 mm;
- (b) 55 to 100% smaller than 4.75 mm;
- (c) 45 to 80% smaller than 2.00 mm;

- (d) 25 to 50% smaller than 0.425 mm; and
- (e) 10 to 25% smaller than 0.180 mm.

Preferably, the aggregate material contains aggregates having different shapes and may have irregular shapes and sizes. For example, each particulate may have different shapes and sizes and irregular edges.

By the term “irregular shape”, it is meant to refer to the aggregate shape being asymmetrical or uneven. The aggregates should contain irregular particles having flaky shape to provide the interlocking effect between each other. For example, natural sand cannot be used because the similar size in three dimensions cannot give satisfactory interlocking effect between each particle.

Preferably, the aggregate material has a water content of 6wt% or less.

Preferably, the aggregate material may be any one selected from the group comprising: manufactured fines, crushed gravel, recycled concrete aggregates, recycled asphalt, slag, and crushed granite. More preferably, the aggregate material used in the present invention is manufactured fines.

Preferably, the cementitious material may be any one or more selected from the group comprising: cement, ground granulated blast furnace slag, and fly ash. In an embodiment of the present invention, the cementitious material is Ordinary Portland Cement. Preferably, the main cementitious material is Ordinary Portland Cement. Supplementary cementitious materials (SCMs) like ground granulated blast furnace slag and fly ash may be used accordingly. In an embodiment of the present invention, the cementitious material is Ordinary Portland Cement.

Preferably, the method further comprising adding at least one additive to the mixture, wherein the at least one additive is any one selected from the group comprising: an accelerator, a retarder, ground granulated blast furnace slag, and fly ash.

Preferably, the method of any of the preceding claims, and further comprising allowing sufficient time for the cement treated base composition to set into a solid mass. The time required may be any typical time known to the skilled person for allowing a CTB composition to set prior to layering a top pavement. Preferably, the total water content of the cement treated base composition is determined by compacting the cement treated base composition to determine the maximum dry density.

In a second aspect of the present invention, there is provided a cement treated base prepared by a method according to the first aspect of the present invention.

Preferably, the cement treated base has a 7 day compressive strength of 2.069 to 7.584 N/mm<sup>2</sup> (300 to 1100 psi), and a 28 day compressive strength of 10.342 N/mm<sup>2</sup> or less ( $\leq 1500$ psi). More preferably, the cement treated base has a 7 day compressive strength of 2.758 to 5.516 N/mm<sup>2</sup> (400 to 800 psi), and a 28 day compressive strength of 6.895 N/mm<sup>2</sup> or less ( $\leq 1000$ psi).

Preferably, the cement treated base has an elastic modulus of less than 3.5 GPa. More preferably, the cement treated base has an elastic modulus of between 0.2 GPa to 2.0 GPa.

By “elastic modulus”, it is meant to refer to the ratio of the force exerted upon a substance or body to the resultant deformation, or the slope of its stress-strain curve in the elastic deformation region. Generally, a lower elastic modulus means higher flexibility – more deformation under certain loading, while higher elastic modulus indicates lower flexibility (or higher stiffness) – less deformation under certain loading.

The cement treated base may be used as a base course for paving any ground, including airport runways or taxiways.

In a third aspect of the present invention, there is provided a cement treated base composition comprising: (a) an aggregate material; and (b) a cementitious material, wherein the aggregate material and the cementitious material has a combined dry mass, and the

composition has a moisture content of between 7.0wt% and 10.5wt% of the combined dry mass.

5 Preferably, the moisture content of the composition is between 8.0wt% to 9.0wt% of the combined dry mass.

Preferably, the amount of cementitious material present in the composition is between 2.0wt% to 6.0wt% of the aggregate material.

10 Preferably, the amount of cementitious material present in the composition is between 3.0wt% to 5.0wt% of the aggregate material.

Preferably, the aggregate material has a particle size distribution in weight percentage of the aggregate material as follows:

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- (i) 100% smaller than 51 mm;
  - (ii) 55 to 100% smaller than 4.75 mm;
  - (iii) 45 to 80% smaller than 2.00 mm;
  - (iv) 25 to 50% smaller than 0.425 mm; and
  - (v) 10 to 25% smaller than 0.180 mm.

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Preferably, the aggregate material may contain aggregates having different shapes. The aggregate material may contain aggregates having different shapes, and may have irregular shapes and sizes.

25 Preferably, the aggregate material has a water content of 6 percentage by weight or less of the aggregate material.

Preferably, the aggregate material is any one selected from the group comprising: manufactured fines, crushed gravel, recycled concrete aggregates, recycled asphalt, slag, and  
30 crushed granite.

Preferably, the cementitious material is any one or more selected from the group comprising: cement, ground granulated blast furnace slag, and fly ash. More preferably, the cementitious material is Ordinary Portland Cement. Preferably, Ordinary Portland Cement is the main component of cementitious material. Other supplementary cementitious materials (SCMs) may be used accordingly.

Preferably, the at least one additive is any one selected from the group comprising: an accelerator, a retarder, ground granulated blast furnace slag, and fly ash.

10 Preferably, when set into a solid mass, the CTB composition has a 7 day compressive strength of 2.069 to 7.584 N/mm<sup>2</sup> (300 to 1100psi), and a 28 day compressive strength of 10.342 N/mm<sup>2</sup> (1500psi) or less.

15 Preferably, when set into a solid mass, the CTB composition has a 7 day compressive strength of 2.758 to 5.516 N/mm<sup>2</sup> (400 to 800psi), and a 28 day compressive strength of 6.895 N/mm<sup>2</sup> (1000psi) or less.

Preferably, when set into a solid mass, the CTB composition has an elastic modulus of less than 3.5 GPa.

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Preferably, when set into a solid mass, the CTB composition has an elastic modulus of between 0.2 GPa to 2.0 GPa.

25 The cement treated base compositions described herein allows cement treated bases to be prepared that has the structural strength of cement treated bases while being more flexible than existing cement treated bases. This combines the advantages from the stabilised-rigid and stabilised-flexible base courses into a single base layer. Thus, the cement treated base disclosed herein provides a base course with appropriate rigidity and flexibility to complement the surface layer to achieve a larger load distribution. This minimises the damage to the surface layer – prolonging the service life of the pavement and reduce the related maintenance work.

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In order that the present invention may be fully understood and readily put into practical effect, there shall now be described by way of non-limitative examples only preferred embodiments of the present invention, the description being with reference to the accompanying illustrative figures.

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In the Figures:

Fig. 1 shows a typical pavement structure.

Fig. 2 shows a flowchart of how to obtain the design mix.

Fig. 3 shows a graph with the gradation of aggregate used.

10 Fig. 4 shows a process of preparing a cement treated base.

Fig. 5 is a compaction curve showing the moisture-density relationship of a first embodiment of the present invention.

Fig. 6 is a compaction curve showing the moisture-density relationship of a second embodiment of the present invention.

15 Fig. 7 is a compaction curve showing the moisture-density relationship of a third embodiment of the present invention.

Fig. 8 is a compaction curve showing the moisture-density relationship of a fourth embodiment of the present invention.

## 20 **Design Mix**

To obtain a CTB composition with the required flexibility and structural strength a design mix needs to be determined and a general method is shown in Fig. 2.

### **(1) Determine moisture-density relations of CTB mixtures**

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The aggregate material (also known as manufactured fines) with the desired gradation is first selected and the water content (also known as moisture content) of the aggregate material is determined. The moisture content of the aggregate must not exceed the final required or desired water content in the cement mix. Typically, natural aggregate materials have a mass ratio of moisture content to aggregate material of 0.5% to 10%. Preferably, aggregates with  
30 a low moisture content not exceeding 6.0% by mass of the dry aggregate is selected.

In obtaining the design mix, the moisture content of the aggregates, should be as low as possible to allow a wider range of water content to be added. The moisture content of the aggregate material can be determined by known methods and devices including using a digital moisture probe, a speedy moisture tester or the oven dry method. The first two devices require several minutes for the testing while the oven dry method requires several hours (typically four hours) of drying. The aggregate material should preferably be kept away from rain to prevent excessive water content in the aggregate material. Alternatively, the aggregate material can be dried prior to mixing. For drying the aggregate material, a possible dehumidifying system has a maximum heating temperature of 150 °C. The dehumidifying time/period depends on the original moisture content of aggregates. The eventual moisture content of aggregates should not exceed 0.5wt%.

The selected aggregates should have a gradation able to provide satisfactory particle packing characteristics. A suitable range of aggregate gradation is shown in Table 1 and is determined by passing the aggregates through sieves of the appropriate sizes as stated. To ensure the interlocking effect among the aggregates, it should mainly comprise irregular particles from crushed gravel and/or stone, free of roots, sod, weeds, and other impurities. The aggregate stockpile should be covered in storage to achieve a homogeneous moisture level for the whole stockpile.

Fig. 3 shows the possible range of gradation for the aggregate material stated in Table 1. The solid lines indicate the acceptable gradation range while the dotted line indicates a specific gradation used in the examples herein, see Table 2. The aggregates should be of irregular shapes and sizes.

Table 1: Aggregate Gradation

| Particle Size | Percentage of Aggregate by Weight |
|---------------|-----------------------------------|
| < 51 mm       | 100                               |
| < 4.75 mm     | 55 – 100                          |
| < 2.00 mm     | 45 – 80                           |

|            |         |
|------------|---------|
| < 0.425 mm | 25 – 50 |
| < 0.180 mm | 10 – 25 |

Table 2: Aggregate Gradation used for examples 1 to 4

| Particle Size | Percentage of Aggregate by Weight |
|---------------|-----------------------------------|
| < 51 mm       | 100                               |
| < 4.75 mm     | 92                                |
| < 2.00 mm     | 62                                |
| < 0.425 mm    | 30                                |
| < 0.180 mm    | 19                                |

A ratio of cementitious materials to the aggregate material is chosen and the required amount of water is added to the mixture of aggregate and cementitious material to produce CTB mixtures with different total water content. A preferred range of cementitious material content is 2wt% to 6wt% of the mass of the dry aggregate material, i.e. 2 to 6 parts cementitious material to 100 parts aggregate material. The resultant mixtures are allowed to harden to produce CTBs with different initial water content. The moisture-density relation of the CTB mixtures is defined according to ASTM D558. By plotting the density of the dried CTB mix and the amount of water content, the maximum dry density and corresponding water content (called the optimum moisture content) can be determined. To determine the optimum moisture content (OMC), it is preferred that the aggregate material used is from the same batch to minimise differences in the water content in the aggregate materials.

The cementitious materials like cement, ground granulated blast furnace slag (GGBFS) and fly ash are used to bind otherwise loose aggregate particles to one another. Cementitious materials provide cohesion and strength for the CTB. The cementitious materials contain negligible amounts of water such that it is not considered to contribute any water content to the CTB mixture. One or more of the supplementary cementitious materials (SCMs) can be combined or blended with ordinary Portland cement to form a mixture for use in the CTB.

The total moisture content of the CTB mixtures includes moisture from the aggregates and added water if required. The moisture content influences the packing properties of solid particles in compaction, and further affects the dry density and strength of the compacted CTB.

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The water used should be of a suitable quality, for example, being largely free of oil, salt, acid, alkali, sugar, vegetable, and other deleterious substances injurious to the finished product.

## (2) Calculation of mix design for a CTB composition

10 The mix design is calculated based on the following formulae, which are defined by

|                                                                                    |     |
|------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)}$                                             | (a) |
| $M_{agg} = \frac{MDD}{(1 + P_c)} \times (1 + \text{Aggregate moisture content}\%)$ | (b) |
| $M_{cem} = M_{agg}^{OD} \times P_c$                                                | (c) |
| $W^{OD} = MDD \times OMC$                                                          | (d) |
| $W = MDD \times OMC - M_{agg}^{OD} \times \text{Aggregate moisture content}\%$     | (e) |

where

$M_{agg}^{OD}$  is the content of oven-dry (OD) aggregate which contains no moisture, kg/m<sup>3</sup>;

$M_{agg}$  is the content of actual aggregate which generally contains some moisture in natural status, kg/m<sup>3</sup>;

15  $MDD$  is the maximum dry density of CTB, kg/m<sup>3</sup>;

$P_c$  is the mass ratio of cement to oven-dry aggregates, i.e. cement percentage, %;

$M_{cem}$  is the cement content, kg/m<sup>3</sup>;

$W^{OD}$  is the additional water content if oven-dry aggregates were used, kg/m<sup>3</sup>.

$W$  is the additional water content (exclusive of moisture from actual aggregate in natural status), kg/m<sup>3</sup>;

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$OMC$  is the optimum moisture content of the CTB, in a mass ratio of total water to the dry solid of cement and aggregates expressed as a %.

An acceptable range for the water content will be  $\pm 1.5$  weight percentage of the optimum water content determined i.e.  $8.5 \pm 1.5\text{wt}\%$ . For better control of the properties of the CTB, the moisture content shall be  $\pm 0.5$  weight percentage of the optimum water content determined. It is preferred to keep the water content in the cement mix as close to the optimum water content to minimise variation in the CTB produced. The mix design gives a composition comprising of the cementitious material, aggregate material and water per cubic meter ( $1\text{m}^3$ ) of compacted CTB.

The preparation of CTB as described herein provides controlled compressive strength that represents appropriate rigidity and flexibility to complement the surface course.

The CTB will to some extent deform concurrently with the surface course under loading. This helps to alleviate the damage to the surface course, leading to a prolonged service life of the pavement and reduce the need for related maintenance work.

### (3) Determination and analysis of compressive strength for CTB laboratory trials

With the mix design obtained in previous section, CTB specimens (diameter: 101.6 mm, height: 116.4 mm) are prepared in the laboratory and tested in accordance with ASTM D1633 to determine the compressive strength. It is preferred to cap the specimens with gypsum plaster because the original rough surface of the CTB specimen affects the compressive strength test results. The compressive strength test is sensitive to the surface of the specimen, and the gypsum plaster minimises the variations. Laboratory trials should be repeated to analyse the deviation and variation. Based on the calculated mix design and analysis of laboratory trials, a final mix design can be provided for plant trials and actual production (Fig. 2).

Further plant and field trials are conducted to verify the performance of the CTB. On the field for trial lay or future construction, each layer of CTB, no greater than 150 mm thick, is laid with a mechanical paver, coupled with the compaction by using a vibratory tandem roller and a pneumatic tyre roller to ensure satisfied compaction degree as well as good surface texture. A number of layers can be added to reach the required thickness for the base course.

A high precision batching system should optimally be used to minimize the variations in weighing the raw materials.

- 5 A dry form of the CTB mixture could be prepared if desired, and the addition of the required amount of water and mixing will produce a cement mixture suitable to use as a CTB mixture.

The amount of water as determined in the design mix is added to either the dry cement mixture prepared above or to the mixture of the aggregate and cementitious material. Typical  
10 cement mixing machines can be used, for example a central mixer in a ready-mix concrete plant, a volumetric mixer on site, or a ready mixed concrete batching system. The mixing is performed until a mix of sufficient homogeneity is obtained. The water can be added in the mixing plant, and the resultant cement mix transported to the site or mixed on site. A suitable cover should be used to minimise water loss or addition in the CTB composition.

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An ambient temperature is acceptable for mixing, preferably 5°C - 40°C. The mixing time for homogeneity depends on the volume of cement mixture and the type of mechanical mixer. In a typical ready-mix concrete plant, the mixing time is typically 45-90 seconds for one to two cubic meter/s ( $1\text{m}^3$  to  $2\text{m}^3$ ) of the CTB composition.

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The CTB composition with the required amount of water prepared as described after being allowed to cure produces a CTB with a 7 day compressive strength in the range of 2.069 to 7.584 N/mm<sup>2</sup> (300-1100 psi) and a 28 day compressive strength of 10.342 N/mm<sup>2</sup> (1500 psi) or less. The elastic modulus of the CTB produced is less than 3.5 GPa, with most of the CTB  
25 compositions producing a corresponding CTB with an elastic modulus of 0.2 GPa to 2.0 GPa.

For comparison, the elastic modulus of a rigid pavement made of Portland cement concrete (PCC) is about 25 GPa to 35 GPa, while the elastic modulus of a flexible pavement made of asphalt concrete is about 2 GPa to 3.5 GPa.

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Preferably, the CTB has a 7 day compressive strength in the range of 2.758 to 5.516 N/mm<sup>2</sup> (400 – 800 psi) and a 28 day compressive strength of 6.895 N/mm<sup>2</sup> or less (1000 psi or less).

A CTB with a compressive strength of this range is suitable for use in airport runways or taxiways.

CTB of other compressive strengths are suitable for other constructions like roads, expressways, and so forth. A CTB with lower compressive strength may be selected as a base course for a normal road with less traffic, while a CTB with higher compressive strength may be used on roads for heavy traffic.

If necessary, some additives and admixtures can be introduced to adjust the properties. A retarder or an accelerator may be used as an admixture to prolong or shorten the hardening time of the CTB respectively. Examples of an accelerator and retarder are calcium nitrate  $[\text{Ca}(\text{NO}_3)_2]$  and molasses respectively.

### Materials and Methods

In all the examples, the raw materials were chosen as described previously. Ordinary Portland Cement (OPC), CEM I 42.5N, was selected as the cementitious materials. The main properties of the cement are shown in Table 3. The gradation of the aggregate material used is as in Table 2.

Table 3: Properties of cement used

| Cement (OPC) | Fineness, $\text{m}^2/\text{kg}$ | Setting time, min |       | Compressive strength, $\text{N}/\text{mm}^2$ |        |
|--------------|----------------------------------|-------------------|-------|----------------------------------------------|--------|
|              |                                  | Initial           | Final | 2-day                                        | 28-day |
| CEM I 42.5   | 338                              | 115               | 135   | 30.7                                         | 61.0   |

ASTM D558 Test method B procedure as described in ASTM D558-11 Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures is used for compacting the CTB mixtures and determining the maximum dry density.

ASTM D1633 Test method A procedure as described in ASTM D1633-00 (2007) Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders with a test specimen of 4.0 in. (101.6 mm) in diameter and 4.584 in. (116.4 mm) in height is used to determine the compressive strength of the specimens. The height to diameter ratio is 1.15.

The elastic modulus is obtained during a compressive strength test.

For each laboratory trial, six specimens were prepared per day. The reported values were the average test results of three specimens for each age.

The following examples of CTB mixtures are provided to exemplify the embodiments of the present invention.

## Examples

### **1. Selection of raw materials**

Raw materials were selected as described previously.

### **2. Determination of moisture-density relations**

The cement percentage was selected to be 3.0% of the dry aggregate mass. Fig. 5 illustrates the compaction curve which shows the relationship between moisture content and dry density of the composition with 3.0% cement according to ASTM D558. From the compaction curve, the optimum moisture content (OMC) is determined to be 8.5%, and the maximum dry density (MDD) is 2025 kg/m<sup>3</sup>. (OMC 8.5% is based on the mass of whole cement composition, i.e. dry CTB materials including cement and aggregate, but do not include water or moisture. MDD 2025 kg/m<sup>3</sup> is also the mass of dry solid CTB materials exclusive of water or moisture.) Values of OMC and MDD for other cement percentages of 3.5%, 4.0% and 5.0% were determined following the same procedure. Table 4 shows the information derived from the compaction curve in Fig. 5 to 8. An acceptable water content range will be about OMC  $\pm$  1.5 wt% for each mix design. The acceptable water content range will thus be 7wt% to 10wt% (or 7.0wt% to 10.3wt% or 7.0wt% to 10.5wt%) of the dry CTB material mass. The dry density of the compacted CTB materials should be equal to or greater than 98% of the respective MDD. To minimise the variation in the quality of CTB samples produced, the water content should be kept as close as possible to the Optimum Moisture Content  $\pm$ 0.5% for each mix design. Thus, the water content range will be 8.0 to 9.0% of the dry CTB material mass.

Table 4: Compaction curve information for examples

| Cement Percentage<br>$P_c$ <sup>(a)</sup> , % | Optimum Moisture<br>Content, OMC, % | Maximum Dry Density,<br>MDD, kg/m <sup>3</sup> |
|-----------------------------------------------|-------------------------------------|------------------------------------------------|
| 3.0%                                          | 8.5%                                | 2025                                           |
| 3.5%                                          | 8.5%                                | 2036                                           |
| 4.0%                                          | 8.5%                                | 2055                                           |
| 5.0%                                          | 8.8%                                | 2065                                           |

<sup>(a)</sup> Cement percentage,  $P_c$ , is the mass ratio of cement to oven-dry (OD) manufactured fines.

### 3. Calculation for mix design

The mix design was calculated based on the formulae, which are defined by

5

|                                                                                    |     |
|------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)}$                                             | (a) |
| $M_{agg} = \frac{MDD}{(1 + P_c)} \times (1 + \text{Aggregate moisture content}\%)$ | (b) |
| $M_{cem} = M_{agg}^{OD} \times P_c$                                                | (c) |
| $W^{OD} = MDD \times OMC$                                                          | (d) |
| $W = MDD \times OMC - M_{agg}^{OD} \times \text{Aggregate moisture content}\%$     | (e) |

where

$M_{agg}^{OD}$  is the content of oven-dry (OD) aggregate which contains no moisture, kg/m<sup>3</sup>;

$M_{agg}$  is the content of actual aggregate which generally contains some moisture in natural status, kg/m<sup>3</sup>;

10  $MDD$  is the maximum dry density of CTB, kg/m<sup>3</sup>;

$P_c$  is the mass ratio of cement to oven-dry aggregates, i.e. cement percentage, %;

$M_{cem}$  is the cement content, kg/m<sup>3</sup>;

$W^{OD}$  is the additional water content if oven-dry aggregates were used, kg/m<sup>3</sup>.

15  $W$  is the additional water content (exclusive of moisture from actual aggregate in natural status), kg/m<sup>3</sup>;

$OMC$  is the optimum moisture content of the CTB, in a mass ratio of total water to the dry solid of cement and aggregates expressed as a %.

If the aggregates were dried prior to use, mix designs for cement percentage 3.0%, 3.5%, 4.0% and 5.0% will be calculated respectively as shown below.

For a cement percentage of 3.0%

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2025}{(1 + 3.0\%)} = 1966 \text{ kg/m}^3$    | (a) |
| $M_{cem} = M_{agg}^{OD} \times P_c = 1966 \text{ kg/m}^3 \times 3.0\% = 59 \text{ kg/m}^3$ | (c) |
| $W^{OD} = MDD \times OMC = 2025 \text{ kg/m}^3 \times 8.5\% = 172 \text{ kg/m}^3$          | (d) |

5 For a cement percentage of 3.5%

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2036}{(1 + 3.5\%)} = 1967 \text{ kg/m}^3$    | (a) |
| $M_{cem} = M_{agg}^{OD} \times P_c = 1967 \text{ kg/m}^3 \times 3.5\% = 69 \text{ kg/m}^3$ | (c) |
| $W^{OD} = MDD \times OMC = 2036 \text{ kg/m}^3 \times 8.5\% = 173 \text{ kg/m}^3$          | (d) |

For a cement percentage of 4.0%

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2055}{(1 + 4.0\%)} = 1976 \text{ kg/m}^3$    | (a) |
| $M_{cem} = M_{agg}^{OD} \times P_c = 1976 \text{ kg/m}^3 \times 4.0\% = 79 \text{ kg/m}^3$ | (c) |
| $W^{OD} = MDD \times OMC = 2055 \text{ kg/m}^3 \times 8.5\% = 175 \text{ kg/m}^3$          | (d) |

10 For a cement percentage of 5.0%

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2065}{(1 + 5.0\%)} = 1967 \text{ kg/m}^3$    | (a) |
| $M_{cem} = M_{agg}^{OD} \times P_c = 1967 \text{ kg/m}^3 \times 5.0\% = 98 \text{ kg/m}^3$ | (c) |
| $W^{OD} = MDD \times OMC = 2065 \text{ kg/m}^3 \times 8.8\% = 182 \text{ kg/m}^3$          | (d) |

The mass ratio of cement to aggregate is calculated by weight of dry aggregate, e.g.  
 $69\text{kg}/1967\text{kg} = 0.035 = 3.5\%$

Total moisture content is calculated by the total weight of the dry solids (Cement+Aggregate), e.g.  $173\text{kg}/(69\text{kg}+1967\text{kg}) = 173/2036 = 8.5\%$ . Here  $2036\text{kg/m}^3$  is also the maximum dry density of CTB which is determined from the moisture-density relations curve (compaction curve).

Hence, the basic mix designs for these examples are shown in Table 5.

**Table 5: Mix designs for Example 1-4**

| CTB Mix Design | Cement Percentage, % | Cement content, $\text{kg/m}^3$ | Manufactured fines (OD), $\text{kg/m}^3$ | Additional Water content, $\text{kg/m}^3$ |
|----------------|----------------------|---------------------------------|------------------------------------------|-------------------------------------------|
| Example 1      | 3.0%                 | 59                              | 1966                                     | 172                                       |
| Example 2      | 3.5%                 | 69                              | 1967                                     | 173                                       |
| Example 3      | 4.0%                 | 79                              | 1976                                     | 175                                       |
| Example 4      | 5.0%                 | 98                              | 1967                                     | 182                                       |

In practice, the aggregates in natural status normally contain some moisture, around 0%-6%. Here we suppose the moisture content to aggregate is 2% by weight of the dry aggregate as an example to show the practical calculation of the batching mix.

|                                                                                               |     |
|-----------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2025}{(1 + 3.0\%)} = 1966 \text{ kg/m}^3$       | (a) |
| $M_{agg} = 1966\text{kg/m}^3 \times (1 + \text{Aggregate moisture } 2\%) = 2005\text{kg/m}^3$ | (b) |
| $M_{cem} = M_{agg}^{OD} \times P_c = 1966 \text{ kg/m}^3 \times 3.0\% = 59 \text{ kg/m}^3$    | (c) |
| $W^{OD} = MDD \times OMC = 2025 \text{ kg/m}^3 \times 8.5\% = 172 \text{ kg/m}^3$             | (d) |
| $W = 172 \text{ kg/m}^3 - 1966 \times 2\% = 133 \text{ kg/m}^3$                               | (e) |

|                                                                                               |     |
|-----------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2036}{(1 + 3.5\%)} = 1967 \text{ kg/m}^3$       | (a) |
| $M_{agg} = 1967\text{kg/m}^3 \times (1 + \text{Aggregate moisture } 2\%) = 2006\text{kg/m}^3$ | (b) |

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| $M_{cem} = M_{agg}^{OD} \times P_c = 1967 \text{ kg/m}^3 \times 3.5\% = 69 \text{ kg/m}^3$ | (c) |
| $W^{OD} = MDD \times OMC = 2036 \text{ kg/m}^3 \times 8.5\% = 173 \text{ kg/m}^3$          | (d) |
| $W = 173 \text{ kg/m}^3 - 1967 \times 2\% = 134 \text{ kg/m}^3$                            | (e) |

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2055}{(1 + 4.0\%)} = 1976 \text{ kg/m}^3$    | (a) |
| $M_{agg} = 1976 \text{ kg/m}^3 \times (1 + \text{Supposed } 2\%) = 2015 \text{ kg/m}^3$    | (b) |
| $M_{cem} = M_{agg}^{OD} \times P_c = 1976 \text{ kg/m}^3 \times 4.0\% = 79 \text{ kg/m}^3$ | (c) |
| $W^{OD} = MDD \times OMC = 2055 \text{ kg/m}^3 \times 8.5\% = 175 \text{ kg/m}^3$          | (d) |
| $W = 175 \text{ kg/m}^3 - 1976 \times 2\% = 135 \text{ kg/m}^3$                            | (e) |

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| $M_{agg}^{OD} = \frac{MDD}{(1 + P_c)} = \frac{2065}{(1 + 5.0\%)} = 1967 \text{ kg/m}^3$    | (a) |
| $M_{agg} = 1967 \text{ kg/m}^3 \times (1 + \text{Supposed } 2\%) = 2006 \text{ kg/m}^3$    | (b) |
| $M_{cem} = M_{agg}^{OD} \times P_c = 1967 \text{ kg/m}^3 \times 5.0\% = 98 \text{ kg/m}^3$ | (c) |
| $W^{OD} = MDD \times OMC = 2065 \text{ kg/m}^3 \times 8.8\% = 182 \text{ kg/m}^3$          | (d) |
| $W = 182 \text{ kg/m}^3 - 1967 \times 2\% = 143 \text{ kg/m}^3$                            | (e) |

Hence the batching mix for example 1 to 4 were tabulated in Table 6, for aggregate material with a determined or supposed moisture content of 2.0wt%. The calculation procedure can be followed for aggregates containing various moisture content.

**Table 6: Batching Mix for Example 1 to 4 used aggregates with moisture of 2%**

| CTB Batching Mix | Cement Percentage, % | Cement content, kg/m <sup>3</sup> | Manufactured fines including moisture of 2%, kg/m <sup>3</sup> | Additional Water content, kg/m <sup>3</sup> |
|------------------|----------------------|-----------------------------------|----------------------------------------------------------------|---------------------------------------------|
| Example 1        | 3.0%                 | 59                                | 2005                                                           | 133                                         |

|           |      |    |      |     |
|-----------|------|----|------|-----|
| Example 2 | 3.5% | 69 | 2006 | 134 |
| Example 3 | 4.0% | 79 | 2015 | 135 |
| Example 4 | 5.0% | 98 | 2006 | 143 |

#### 4. Determination of compressive strength for CTB laboratory trials

With the mix design in Table 5, CTB specimens (diameter: 101.6 mm, height: 116.4 mm) were prepared and tested in accordance with ASTM D558 and D1633 to determine the compressive strength and is shown in Table 7 to 10.

It can be observed in Table 7 that the CTB prepared with cement percentage 3.0% can achieve a 7-day compressive strength ( $f_c$ ) range from 2.069 N/mm<sup>2</sup> to 4.826 N/mm<sup>2</sup> (300-700psi), and a 28-day compressive strength equal to or less than 6.206 N/mm<sup>2</sup> ( $\leq 900$ psi). The 28-day elastic modulus is between 0.2 GPa to 2.0 GPa.

As shown in Table 8 to 10, the CTB prepared with cement percentage of 3.5%, 4.0% and 5.0% can achieve 7-day compressive strength ( $f_c$ ) range from 2.758 N/mm<sup>2</sup> to 5.516 N/mm<sup>2</sup> (400-800psi), 3.448 N/mm<sup>2</sup> to 6.206 N/mm<sup>2</sup> (500psi to 900psi), and 4.137 N/mm<sup>2</sup> to 7.584 N/mm<sup>2</sup> (600-1100psi), respectively. They provide 28-day compressive strength equal to or less than 6.895 N/mm<sup>2</sup> ( $\leq 1000$ psi), 7.584 N/mm<sup>2</sup> ( $\leq 1100$ psi), and 10.342 N/mm<sup>2</sup> ( $\leq 1500$ psi). The 28-day elastic modulus is between 0.2 GPa to 2.0 GPa for all the examples.

Table 7: Compressive strength of Example 1 for laboratory trials

| Experiment No.                   | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | Average value | Standard deviation |
|----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------|--------------------|
| 7-day $f_c$ , N/mm <sup>2</sup>  | 2.779 | 2.536 | 2.918 | 2.545 | 2.613 | 2.582 | 2.594 | 2.519 | 2.712 | 2.640         | 0.133              |
| 28-day $f_c$ , N/mm <sup>2</sup> | 3.773 | 3.794 | 4.336 | 3.890 | 3.819 | 4.041 | 4.028 | 4.051 | 3.935 | 3.963         | 0.176              |
| 28-day Elastic                   | 0.27  | 0.34  | 0.31  | 0.29  | 0.29  | 0.40  | 0.54  | 0.40  | 0.36  | 0.36          | 0.09               |

|                 |  |  |  |  |  |  |  |  |  |  |  |
|-----------------|--|--|--|--|--|--|--|--|--|--|--|
| modulus,<br>GPa |  |  |  |  |  |  |  |  |  |  |  |
|-----------------|--|--|--|--|--|--|--|--|--|--|--|

Table 8: Compressive strength of Example 2 for laboratory trials

| Experiment<br>No.                    | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | Average<br>value | Standard<br>deviation |
|--------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------------------|-----------------------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>   | 3.499 | 3.294 | 3.539 | 3.463 | 3.138 | 3.469 | 3.296 | 3.218 | 3.131 | 3.339            | 0.158                 |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup>  | 5.613 | 5.576 | 5.791 | 5.592 | 5.527 | 5.334 | 5.640 | 5.420 | 5.100 | 5.510            | 0.202                 |
| 28-day<br>Elastic<br>modulus,<br>GPa | 0.72  | 0.62  | 0.66  | 0.48  | 0.52  | 0.46  | 0.75  | 0.66  | 0.56  | 0.60             | 0.10                  |

**Table 9: Compressive strength of Example 3 for laboratory trials**

| Experiment No.                   | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | Average value | Standard deviation |
|----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------|--------------------|
| 7-day $f_c$ , N/mm <sup>2</sup>  | 4.341 | 4.135 | 4.640 | 4.258 | 4.483 | 4.242 | 4.425 | 4.009 | 4.260 | 4.310         | 0.188              |
| 28-day $f_c$ , N/mm <sup>2</sup> | 6.827 | 6.718 | 7.178 | 6.867 | 6.922 | 6.869 | 6.876 | 6.427 | 6.884 | 6.841         | 0.197              |
| 28-day Elastic modulus, GPa      | 0.77  | 0.64  | 0.94  | 0.79  | 0.91  | 0.65  | 0.84  | 0.61  | 0.72  | 0.76          | 0.12               |

**Table 10: Compressive strength of Example 4 for laboratory trials**

| Experiment No.                   | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | Average value | Standard deviation |
|----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------|--------------------|
| 7-day $f_c$ , N/mm <sup>2</sup>  | 5.918 | 6.280 | 5.877 | 5.848 | 6.283 | 5.636 | 5.717 | 6.226 | 5.943 | 5.959         | 0.244              |
| 28-day $f_c$ , N/mm <sup>2</sup> | 7.418 | 8.192 | 7.099 | 7.998 | 8.235 | 7.608 | 8.049 | 9.042 | 8.093 | 7.970         | 0.557              |
| 28-day Elastic modulus, GPa      | 0.76  | 0.88  | 1.19  | 0.97  | 1.30  | 1.22  | 1.12  | 0.80  | 0.79  | 1.00          | 0.21               |

5

## 5. Determination of compressive strength for CTB Plant trials

Plant trials of CTB prepared in these examples were conducted. Fourteen trial mixes were carried out on different days for each mix design to analyse the variation of compressive strength in a practical batching system. The compressive strength was tested and presented

in Table 11 to 14. It can be observed that at 7 days, the compressive strength of CTB with a cement percentage of 3.0% was within the range from 2.069 N/mm<sup>2</sup> to 4.826 N/mm<sup>2</sup> (300-700psi). Meanwhile, the results gave the compressive strength of equal to or less than 6.206 N/mm<sup>2</sup> ( $\leq$  900psi) and an elastic modulus of between 0.2 GPa to 2.0 GPa at 28 days. The average and standard deviation for the compressive strength and elastic modulus are provided as well. It indicates that the quality of CTB plant trials was consistent and in agreement with the laboratory trials.

Table 12 to 14 shown that CTB plant trials using cement percentage of 3.5%, 4.0% and 5.0% also achieved their target range of compressive strength and elastic modulus.

Table 11: Compressive strength of Example 1 for plant trials

| Experiment No.                      | 1     | 2     | 3     | 4     | 5     | 6     | 7      | 8     | 9     | 10    |
|-------------------------------------|-------|-------|-------|-------|-------|-------|--------|-------|-------|-------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 3.533 | 2.877 | 3.064 | 2.837 | 2.720 | 2.523 | 2.7977 | 3.014 | 2.961 | 2.809 |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 4.518 | 4.294 | 3.748 | 4.240 | 3.968 | 3.917 | 4.042  | 3.934 | 4.187 | 4.205 |
| 28-day Elastic<br>modulus, GPa      | 0.57  | 0.36  | 0.54  | 0.24  | 0.41  | 0.58  | 0.51   | 0.42  | 0.24  | 0.31  |

Table 11: Compressive strength of Example 1 for plant trials

| Experiment No.                      | 11    | 12    | 13    | 14    | Average | Standard Deviation |
|-------------------------------------|-------|-------|-------|-------|---------|--------------------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 2.685 | 2.786 | 2.670 | 2.360 | 2.844   | 0.277              |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 4.057 | 3.743 | 3.859 | 4.158 | 4.062   | 0.220              |
| 28-day Elastic<br>modulus, GPa      | 0.29  | 0.51  | 0.25  | 0.55  | 0.41    | 0.13               |

Table 12: Compressive strength of Example 2 for plant trials

| Experiment No.                      | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 3.186 | 3.615 | 3.345 | 3.332 | 2.929 | 3.294 | 3.111 | 3.087 | 3.161 | 3.309 |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 4.634 | 5.096 | 4.627 | 4.853 | 4.304 | 4.812 | 4.535 | 4.595 | 4.962 | 4.990 |
| 28-day Elastic<br>modulus, GPa      | 0.63  | 0.70  | 0.60  | 0.38  | 0.56  | 0.38  | 0.46  | 0.48  | 0.56  | 0.54  |

Table 12: Compressive strength of Example 2 for plant trials

| Experiment No.                      | 11    | 12    | 13    | 14    | Average | Standard Deviation |
|-------------------------------------|-------|-------|-------|-------|---------|--------------------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 3.183 | 3.111 | 3.262 | 3.355 | 3.234   | 0.163              |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 5.107 | 5.128 | 5.110 | 5.087 | 4.846   | 0.266              |
| 28-day Elastic<br>modulus, GPa      | 0.70  | 0.56  | 0.44  | 0.40  | 0.53    | 0.11               |

5 Table 13: Compressive strength of Example 3 for plant trials

| Experiment No.                      | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 4.258 | 3.930 | 4.242 | 4.256 | 4.355 | 4.727 | 4.304 | 4.545 | 4.006 | 4.315 |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 6.527 | 6.183 | 6.594 | 6.211 | 6.003 | 6.316 | 5.757 | 5.912 | 5.652 | 6.015 |
| 28-day Elastic<br>modulus, GPa      | 0.79  | 0.62  | 0.84  | 0.62  | 0.55  | 0.73  | 0.51  | 0.71  | 0.51  | 0.62  |

**Table 13: Compressive strength of Example 3 for plant trials**

| Experiment No.                      | 11    | 12    | 13    | 14    | Average | Standard Deviation |
|-------------------------------------|-------|-------|-------|-------|---------|--------------------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 4.183 | 3.911 | 4.262 | 4.355 | 4.261   | 0.219              |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 6.094 | 5.761 | 5.825 | 6.025 | 6.063   | 0.283              |
| 28-day Elastic<br>modulus, GPa      | 0.78  | 0.58  | 0.52  | 0.81  | 0.66    | 0.12               |

**Table 14: Compressive strength of Example 4 for plant trials**

| Experiment No.                      | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 5.327 | 5.902 | 5.615 | 5.316 | 5.328 | 5.332 | 6.020 | 5.939 | 5.560 | 6.495 |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 7.195 | 7.254 | 8.201 | 7.101 | 7.845 | 7.458 | 7.083 | 7.063 | 7.468 | 9.208 |
| 28-day Elastic<br>modulus, GPa      | 1.11  | 1.23  | 1.51  | 0.95  | 0.73  | 1.17  | 1.53  | 0.96  | 1.37  | 0.99  |

5 **Table 14: Compressive strength of Example 4 for plant trials**

| Experiment No.                      | 11    | 12    | 13    | 14    | Average | Standard Deviation |
|-------------------------------------|-------|-------|-------|-------|---------|--------------------|
| 7-day $f_c$ ,<br>N/mm <sup>2</sup>  | 5.609 | 6.229 | 5.541 | 6.013 | 5.730   | 0.374              |
| 28-day $f_c$ ,<br>N/mm <sup>2</sup> | 8.501 | 9.308 | 7.708 | 7.947 | 7.810   | 0.753              |
| 28-day Elastic<br>modulus, GPa      | 0.86  | 1.29  | 1.04  | 1.43  | 1.16    | 0.25               |

### Field trial lay

To further assess the performance of CTB, a field trial lay was conducted using a cement percentage of 3.5%. The field trial lay consisted of three layers, and used 46.38 m<sup>3</sup> in total of the CTB prepared in this example, as shown in Table 15.

10

Table 15: Dimension of CTB layers of Example 2 for field trial lay

| Dimension                  | Bottom layer      | Middle layer         | Top layer            |
|----------------------------|-------------------|----------------------|----------------------|
| Width × Length × Thickness | 5m×30m×120mm      | 4.4m×30m×120mm       | 3.8m×30m×110mm       |
| Volume, m <sup>3</sup>     | 18 m <sup>3</sup> | 15.84 m <sup>3</sup> | 12.54 m <sup>3</sup> |

The compressive strength at both 7 days and 28 days, and the elastic modulus at 28 days of the field trial specimens is shown in Table 16.

Table 16: Compressive strength of Example 2 for field trial lay

| Sample   | 7d compressive strength, N/mm <sup>2</sup> | 28d compressive strength, N/mm <sup>2</sup> | 28d Elastic modulus, |
|----------|--------------------------------------------|---------------------------------------------|----------------------|
| Sample 1 | 3.810                                      | 5.124                                       | 0.52                 |
| Sample 2 | 3.686                                      | 5.568                                       | 0.59                 |
| Sample 3 | 3.874                                      | 5.625                                       | 0.54                 |

The trials in the example show that the CTB in this example can achieve the compressive strength range from 2.758 to 5.516 N/mm<sup>2</sup> (400-800psi) at 7 days, and equal to or less than 6.895 N/mm<sup>2</sup> (≤1000psi) and an elastic modulus of less than 3.5 GPa, or even more particularly between 0.2 GPa to 2.0 GPa. The controlled compressive strength indicates appropriate rigidity.

With different cement percentage, different design mix can be determined and calculated as exemplified and described herein. Table 17 shows the different design mix that can be obtained with different cement percentage. Thus with the aggregate materials, a cement percentage of 2% to 8% (preferably, the amount may be 2%-6%) by mass of the dry aggregate, and a moisture content of 7.0 to 10.5% by mass of the combined combin of the dry aggregate and cementitious materials will give a mixture that produces a CTB with the required strength yet is flexible. Table 18 summarises the compressive strength of the Examples shown.

**Table 17: CTB Composition with different cement percentages**

| Example   | Cement Percentage, % | Cement content, kg/m <sup>3</sup> | Manufactured fines (OD), kg/m <sup>3</sup> | Additional Water content, kg/m <sup>3</sup> | Optimum Moisture Content / % |
|-----------|----------------------|-----------------------------------|--------------------------------------------|---------------------------------------------|------------------------------|
| Example 1 | 3.0                  | 59                                | 1966                                       | 172                                         | 8.5                          |
| Example 2 | 3.5                  | 69                                | 1967                                       | 173                                         | 8.5                          |
| Example 3 | 4.0                  | 79                                | 1976                                       | 175                                         | 8.5                          |
| Example 4 | 5.0                  | 98                                | 1967                                       | 182                                         | 8.8                          |

**Table 18: CTB Examples and compressive strength (N/mm<sup>2</sup>)**

| Mix Design | 7-day compressive strength, N/mm <sup>2</sup> (psi) | 28-day compressive strength, N/mm <sup>2</sup> (psi) |
|------------|-----------------------------------------------------|------------------------------------------------------|
| Example 1  | 2.069 to 4.826 (300 to 700)                         | ≤ 6.206 ( ≤ 900)                                     |
| Example 2  | 2.758 to 5.516 (400 to 800)                         | ≤ 6.895 ( ≤ 1000)                                    |
| Example 3  | 3.448 to 6.206 (500 to 900)                         | ≤ 7.584 ( ≤ 1100)                                    |
| Example 4  | 4.137 to 7.584 (600 to 1100)                        | ≤ 10.342 ( ≤ 1500)                                   |

- 5 The workable range of the CTB composition comprises 100 parts of aggregate material, 2 to 6 parts of cementitious materials (a mass ratio of 2.0wt% to 6.0wt%) or 3 to 5 parts (3.0wt% to 5.0wt%), and an optimum water content of 8.5wt% to 8.8wt% of the combined dry mass of the aggregate material and cementitious material.
- 10 Thus, a workable range for the water content will be from 7.0wt% to 10.0wt% for an optimum moisture content of 8.5wt% and 7.3wt% to 10.3wt% for an optimum moisture content of 8.8wt%. It is conceivable that with a higher cement percentage the water content required is

higher, a possible workable range for the water content is thus 7.0wt% to 10.5wt% of the combined dry mass of the aggregate and cementitious materials.

5 In an embodiment the range of water content is within 0.5wt% of the optimum moisture content. Thus, a range of 8.0wt% to 9.0wt%, 8.3wt% to 9.3wt%, or 8.0wt% to 9.3wt% will produce less variation in the properties of the CTB.

10 The cement mixtures described herein allows a cement treated base to be prepared which has both compressive strength and flexibility. This allows the cement treated base prepared by the embodiments of the present invention to be more versatile and useful than existing base courses. The cement treated base described herein minimises the damage to the surface layer – prolonging the service life of the pavement and reducing the related maintenance work.

15 Whilst there has been described in the foregoing description preferred embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations or modifications in details of design or construction may be made without departing from the present invention.

20

## Claims

1. A method of preparing a cement treated base composition, the method comprising:

(a) providing an amount of aggregate material and an amount of cementitious material, the aggregate material and cementitious material having a combined dry mass;

(b) mixing the aggregate material and the cementitious material to form a mixture; and

(c) if necessary, providing an amount of water to the mixture to form the composition, wherein a moisture content of the composition is between 7.0wt% and 10.5wt% of the combined dry mass, wherein the aggregate material has a particle size distribution in weight percentage of the aggregate material as follows:

(d) 100% smaller than 51 mm;

(e) 55 to 100% smaller than 4.75 mm;

(f) 45 to 80% smaller than 2.00 mm;

(g) 25 to 50% smaller than 0.425 mm; and

(i) 10 to 25% smaller than 0.180 mm.

2. The method according to claim 1, wherein the moisture content of the composition is between 8.0wt% to 9.0wt% of the combined dry mass.

3. The method according to any one of claims 1 or 2, wherein the amount of cementitious material present in the composition is between 2.0wt% to 6.0wt% of the aggregate material.

4. The method according to claim 3, wherein the amount of cementitious material present in the composition is between 3.0wt% to 5.0wt% of the aggregate material.

5. The method according to any of the preceding claims, wherein the aggregate material comprising particles having irregular shapes and sizes.

6. The method according to any of the preceding claims, wherein the aggregate material has a water content of 6wt% or less.

7. The method according to any of the preceding claims, wherein the aggregate material is any one selected from the group comprising: manufactured fines, crushed gravel, recycled concrete aggregates, recycled asphalt, slag, and crushed granite.

8. The method according to any of the preceding claims, wherein the cementitious material is any one selected from the group comprising: cement, ground granulated blast furnace slag, and fly ash.

9. The method according to claim 8, wherein the cement is Ordinary Portland Cement.

10. The method according to any of the preceding claims, further comprising adding at least one additive to the mixture, wherein the at least one additive is any one selected from the group comprising: an accelerator, a retarder, ground granulated blast furnace slag, and fly ash.

11. A method of preparing a cement treated base comprising the method of any of the preceding claims, and further comprising allowing sufficient time for the cement treated base composition to set into a solid mass.

12. A cement treated base prepared by a method according to claim 11.

13. The cement treated base according to claim 12, wherein the cement treated base has a 7 day compressive strength of  $2.069 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  to  $7.584 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as  $2.069 \text{ N/mm}^2$  to  $7.584 \text{ N/mm}^2$  or 300 to 1100psi), and a 28 day compressive strength of  $1.0342 \times 10^7 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as  $10.342 \text{ N/mm}^2$  or 1500psi) or less.

14. The cement treated base according to claim 12, wherein the cement treated base has a 7 day compressive strength of  $2.758 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  to  $5.516 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as  $2.758 \text{ N/mm}^2$  to  $5.516 \text{ N/mm}^2$  or 400 to 800psi), and a 28 day compressive strength of  $6.895 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as  $6.895 \text{ N/mm}^2$  or 1000psi) or less.

15. The cement treated base according to claim 12, wherein the cement treated base has an elastic modulus of less than  $3.5 \times 10^9 \text{ m}^{-1} \text{ kg s}^{-2}$  (3.5 GPa).

16. The cement treated base according to claim 12, wherein the cement treated base has an elastic modulus of between  $0.2 \times 10^9 \text{ m}^{-1} \text{ kg s}^{-2}$  to  $2.0 \times 10^9 \text{ m}^{-1} \text{ kg s}^{-2}$  (0.2 GPa to 2.0 GPa).

17. Use of a cement treated base according to any one of claims 12 to 16 as a base course for airport runways or taxiways.

18. A cement treated base composition comprising:

(a) an aggregate material, wherein the aggregate material has a particle size distribution in weight percentage of the aggregate material as follows:

- i) 100% smaller than 51 mm;
- ii) 55 to 100% smaller than 4.75 mm;
- iii) 45 to 80% smaller than 2.00 mm;
- iv) 25 to 50% smaller than 0.425 mm; and
- v) 10 to 25% smaller than 0.180 mm; and

(b) a cementitious material,

wherein the aggregate material and the cementitious material has a combined dry mass, and the composition has a moisture content of between 7.0wt% and 10.5wt% of the combined dry mass.

19. The cement treated base composition according to claim 18, wherein the moisture content of the composition is between 8.0wt% to 9.0wt% of the combined dry mass.

5 20. The cement treated base composition according to any one of claims 18 or 19, wherein the amount of cementitious material present in the composition is between 2.0wt% to 6.0wt% of the aggregate material.

21. The cement treated base composition according to any one of claims 18 to 20,  
10 wherein the amount of cementitious material present in the composition is between 3.0wt% to 5.0wt% of the aggregate material.

22. The cement treated base composition according to any of claims 18 to 21, wherein the aggregate material contains particles having irregular shapes and sizes.

15 23. The cement treated base composition according to any of claims 18 to 22, wherein the aggregate material has a water content of 6wt% or less.

24. The cement treated base composition according to any of claims 18 to 23,  
20 wherein the aggregate material is any one selected from the group comprising: manufactured fines, crushed gravel, stone recycled concrete, recycled asphalt, slag, and crushed granite.

25. The cement treated base composition according to any of claims 18 to 24,  
25 wherein the cementitious material is any one selected from the group comprising: cement, ground granulated blast furnace slag, and fly ash.

26. The cement treated base composition according to claim 25, wherein the cement is Ordinary Portland Cement.

30 27. The cement treated base composition according to any of claims 18 to 26, further comprising at least one additive, wherein the at least one additive is any one selected

from the group comprising: an accelerator, a retarder, ground granulated blast furnace slag, and fly ash.

28. The cement treated base composition according to claim 18, wherein when set into a solid mass has a 7 day compressive strength of  $2.069 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  to  $7.584 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as 2.069 N/mm<sup>2</sup> to 7.584 N/mm<sup>2</sup> or 300 to 1100psi), and a 28 day compressive strength of  $1.0342 \times 10^7 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as 10.342 N/mm<sup>2</sup> or 1500psi) or less.

29. The cement treated base composition according to claim 18, wherein when set into a solid mass has a 7 day compressive strength of  $2.758 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  to  $5.516 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as 2.758 N/mm<sup>2</sup> to 5.516 N/mm<sup>2</sup> or 400 to 800psi), and a 28 day compressive strength of  $6.895 \times 10^6 \text{ m}^{-1} \text{ kg s}^{-2}$  (also expressed as 6.895 N/mm<sup>2</sup> or 1000psi) or less.

30. The cement treated base composition according to claim 18, wherein when set into a solid mass has an elastic modulus of less than  $3.5 \times 10^9 \text{ m}^{-1} \text{ kg s}^{-2}$  (3.5 GPa).

31. The cement treated base composition according to claim 18, wherein when set into a solid mass has an elastic modulus of between  $0.2 \times 10^9 \text{ m}^{-1} \text{ kg s}^{-2}$  to  $2.0 \times 10^9 \text{ m}^{-1} \text{ kg s}^{-2}$  (0.2 GPa to 2.0 GPa).